Fermi National Accelerator Laboratory

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Preliminary Design Note for a Direct Coupled 200,000 Amp Neutrino Horn Power Supply with Energy Recovery

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ABSTRACT

The availability of high current, (several thousand amperes) silicon controlled rectifiers and high current, low loss capacitors make it practical to design a direct coupled energy discharge power supply for the neutrino horns in the proposed NuMI facility at Fermilab. The neutrino horns require a continuous pulse train of 200,000 A and 1 msec duration at a pulse period of 1.5 seconds. This high current pulse train yields a system load current of about 9,000 A rms. Using a high power coupling transformer between the energy stored in a capacitor bank and the horns is very expensive because the transformer secondary winding would have to be rated for 9,000 A rms at about 1400 Vpk. The transformer would also add leakage inductance to the discharge circuit, take up a substantial amount of floor space and make stored energy recovery from the horns less effective or maybe even impractical. The transformer would need a reset winding to remove the high remnant magnet field in the transformer steel which is caused by the unipolar discharge pulses.

A coupling transformer is practical for high voltage loads, but the horns operate at a relatively low voltage of about 1400 V, which makes direct coupling very attractive.

This note describes a preliminary design for a direct coupled system. From the design notes we can conclude that direct coupling is economical, practical, relatively simple, can use energy recovery and does not require materials or equipment that is hard to obtain. The charging power supply could be two standard (Fermilab) 240 kW beamline power supplies connected in series and grounded at the midpoint. The capacitor bank, switches, transmission line and controls can be most economically assembled in house. We may conclude that it is desirable to build a direct coupled neutrino horn power supply system and to connect both horns in series.

1.0 CIRCUIT DESIGN REQUIREMENTS AND CHOICES

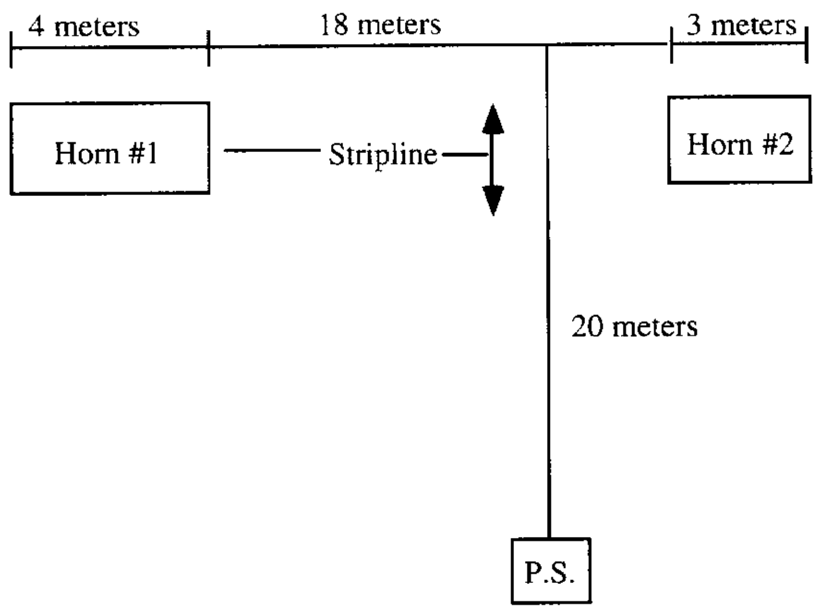
The neutrino horns require a continuous dc current pulse train with a pulse period of 1.5 sec and a peak value that does not change more than 10% during a beam spill duration of 1 msec. The minimum required peak current value during beam spill is 200,000 A.

As a safety margin we will choose a peak current $\hat{i}$ that stays between 200,000 A and 220,000 A for a duration of 1.5 msec. The circuit used for the estimate is a basic LC damped discharge circuit (Fig. 1) which yields the required peak current when a switch releases stored energy from a charged capacitor bank to the horns. The horns are connected in series. A low inductance stripline connects the horns to the capacitor bank. The estimated circuit parameters are summarized below:

System Parameters

R	=	5×10^{-4} Ohm (each horn)
L	=	1.5×10^{-6} Henry (each horn)
$\hat{i}$	=	200,000 Amps minimum during 1.5 msec
beam spill duration	=	1 msec
$\hat{i}$	$\leq$	10% deviation during spill
pulse period	=	1.5 seconds, continuous

Estimated equipment distances are shown below:



Summary of the neutrino horns circuit inductance L and resistance R

		L	R	
1	2-horns	3 μH	1 mΩ	
2	transmission line power supply to center of horns, 20 m distance between horns, 20 m	 2 μH 2 μH	 0.247 mΩ 0.247 mΩ	
3	power supply capacitor bank	1 μH*	0.03 mΩ	Est.*
	TOTAL	**8 μH**	**1.524 mΩ**	

2.0 EQUIVALENT HORN DISCHARGE CIRCUIT USED FOR ESTIMATES

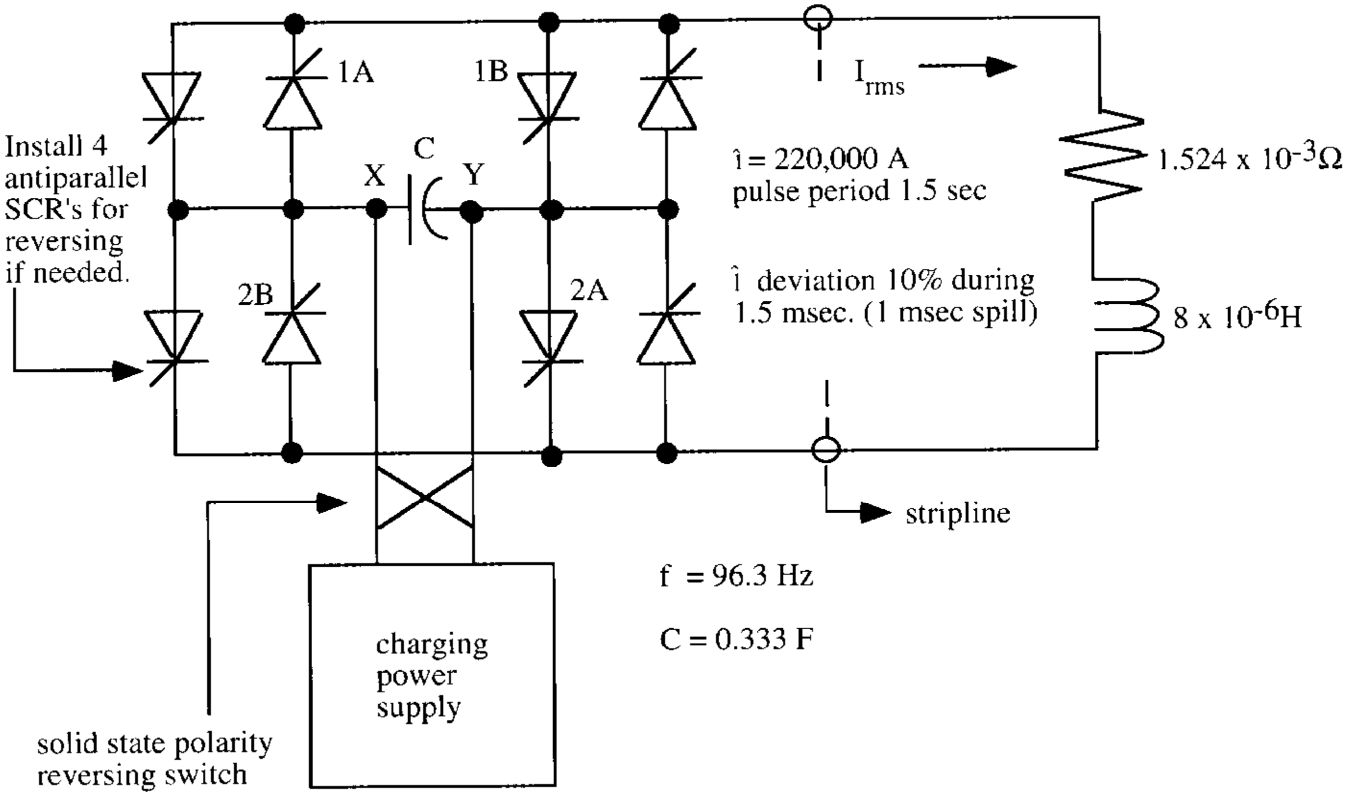
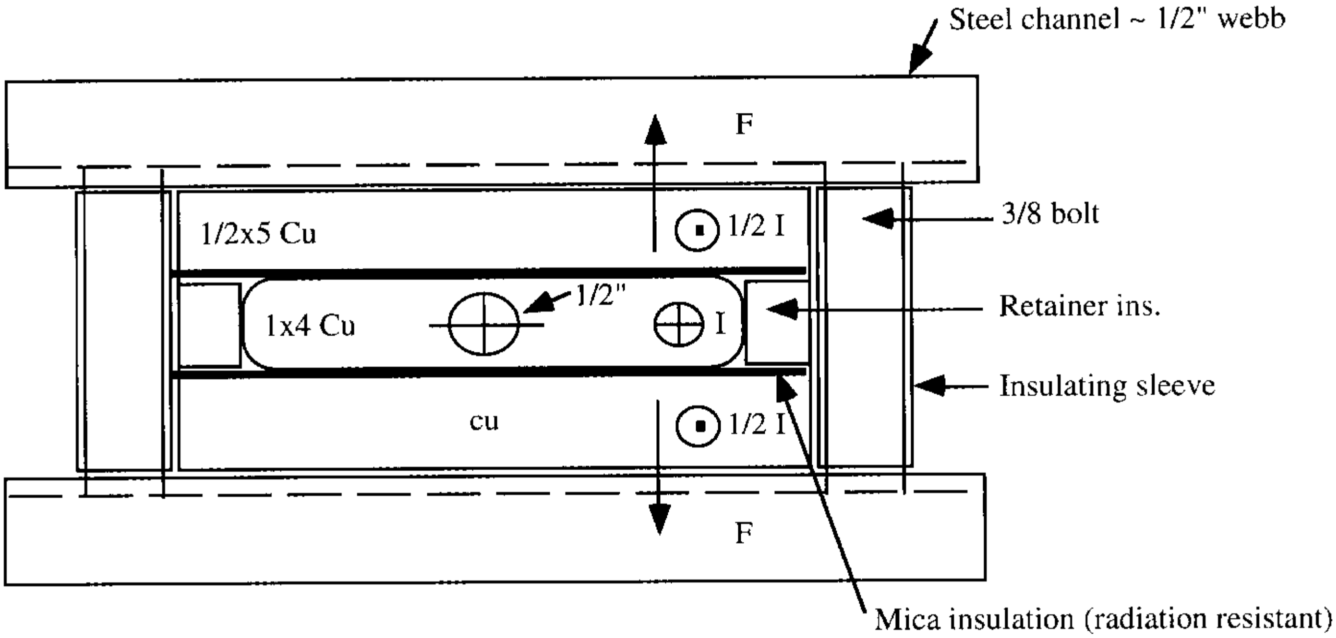


Figure 1. Basic horn discharge circuit with charge recovery

The equivalent circuit for the neutrino horns is shown in Fig. 1. Capacitor bank C is charged from a dc charging power supply via a charge polarity reversing switch, which initially charges bipolar capacitor C positive at X. The charge at C is released by firing all 4 SCR's 1A through 2B. Only SCR 1A and 2A will stay on since SCR 1B and 2B are reverse biased. C discharges now through the horns and some of the stored energy will be recaptured at C with Y being positive. This recovered charge direction is detected at the charge polarity reversing switch and charge will now be added to C at Y positive for the next pulse. Again, firing all discharge SCR's will now cause only discharge SCR 1B and 2B to carry the discharge current. The charge polarity at C will thus change from pulse to pulse. This scheme yields the maximum amount of recovered charge and the lowest possible rms current values (lowest losses) in the discharge loop. Installation of antiparallel SCR's (Fig. 1) can yield horn current polarity reversal if needed. The capacitor bank and discharge SCR's need to be broken into possibly 8 sections to meet the component current ratings and capacitor case rupture energy ratings. The connections between the capacitor bank and horns can be made with a stripline as proposed in Fig. 2.



F	=	1500 kg/m (force)
L	=	0.1 μH/m (inductance)
R	=	12.34 x 10^{-6} Ω/m (resistance)
W	=	55 kg/m (weight)
T	=	80°C (temperature)
Rad.	=	10^{10} Ergs/cm^2 (rad. damage)
Insulation	=	105°C (temperature rating)
$	=	250 $/m (cost)

(Design estimates by S. Orr)

Figure 2. Watercooled stripline for neutrino horns at $\hat{I}$ = 220,000 A.

From this circuit information and the required current pulses, we can estimate the operating frequency and component ratings.

3.0 CALCULATIONS OF CIRCUIT PARAMETERS AND COMPONENTS

3.1 Calculate the required discharge frequency for Fig. 1

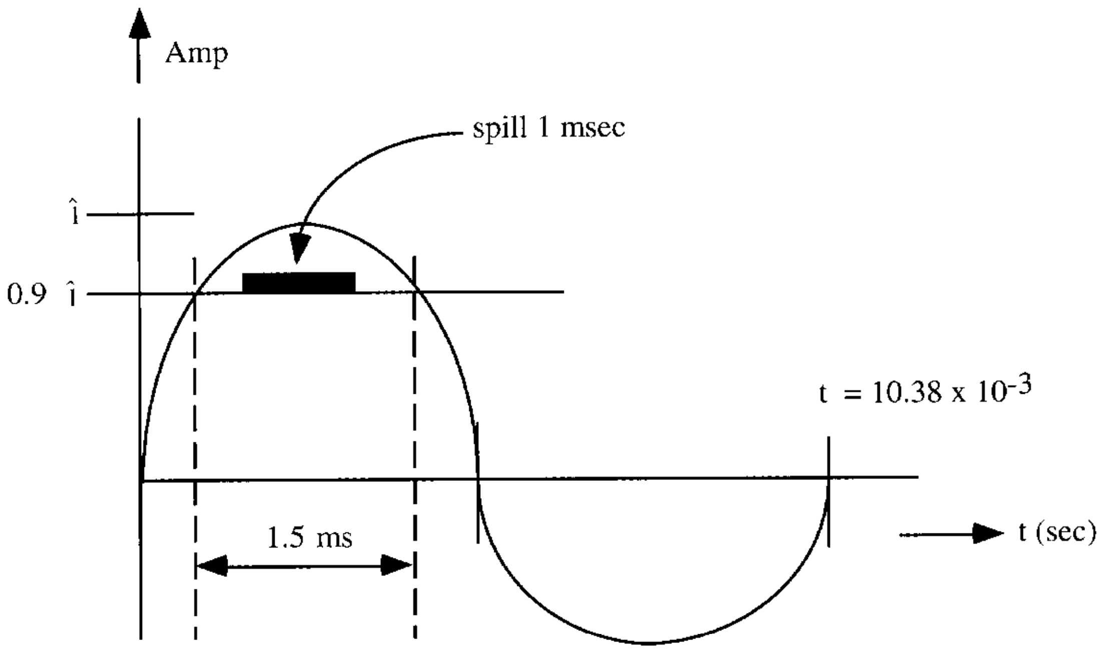


Figure 3. Discharge current of Figure 1.

1.5 msec equals 52°.

$$t = \frac{360}{52} \times 1.5 = 10.38 \times 10^{-3}\ \text{sec.}$$

$$f = \frac{1}{t} = 96.3\,\text{Hz}$$

3.2 Calculate the required value C which yields f = 96.3 Hz for Figure 1.

The ringing frequency of a damped oscillatory circuit is:

$$f=\frac{1}{2\pi}\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}$$

$$96.3=\frac{1}{2\pi}\sqrt{\frac{1}{8x10^{-6}C}-\frac{(1.524x10^{-3})^2}{4(8x10^{-6})^2}}$$

$$605=\sqrt{\frac{125x10^3}{C}-9.1x10^3}$$

$$36.6=\frac{12.5}{C}-0.91$$

$$C=0.333F$$

3.3 Calculate the required capacitor charge voltage V which yields a peak current $\hat{\imath}$ = 220,000A into the horns.

The instantaneous current value, i, in an oscillatory RLC circuit as in Fig. 1 is:

$i = 2\pi\ fCV\ e^{-Rt/2L} \sin 2\ \pi ft$

$2\pi\ fCV$ is the undamped peak current value.

$e^{-Rt/2L}$ is the damping factor (δ).

$\sin 2\pi ft$ is the oscillatory function

t is time

The first peak current, $\hat{\imath}$, occurs at 1/4 period.

$\hat{\imath} = 2\pi\ fCV\ e^{-R/8Lf}$

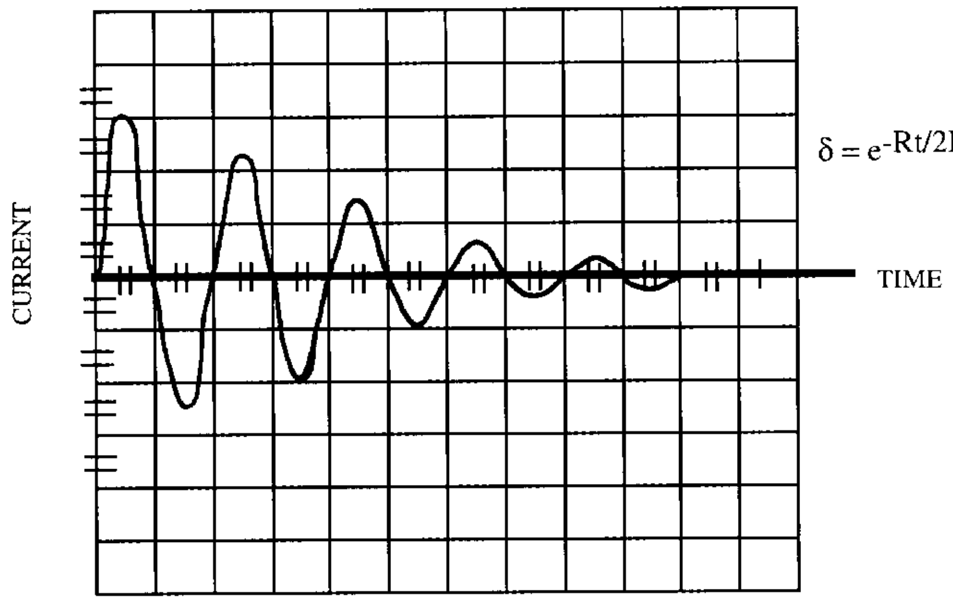


Figure 4: Damped oscillation of RLC circuit.

For Fig. 1: $\delta_{1/4} = e^{-1.524x10^{-3}/8x8x10^{-6}x96.3}$

$\delta_{1/4} = e^{-0.247} = 0.78$

The required charge voltage is:

$220{,}000 = 2\pi \text{ x } 96.3 \text{ x } 0.333 \text{ x V x } 0.78$

$V = 1400$ V

3.4 Conclusions

A charge voltage of 1400 V into 0.33 F yields 220,000 A peak into the two horns connected in series.

The recovered charge voltage has a damping value of:

$\delta_{1/2} = 0.6$

The recovered charge voltage = 850 V.

3.5 Calculation of the rms value of the horn current pulse train

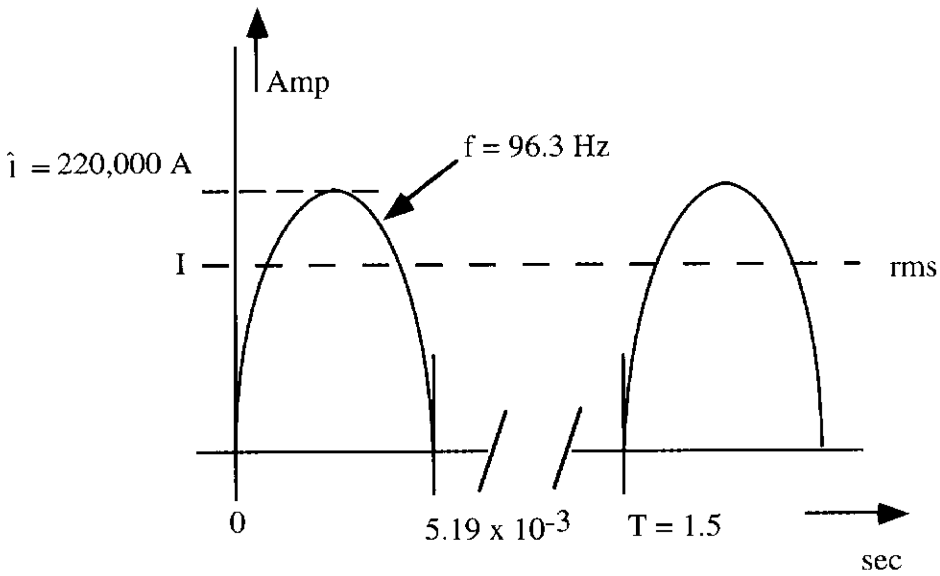


Figure 5. Continuous current pulses through the horns.

The rms value of the current pulse train, shown in Fig. 5, is the same as for the pulse train shown in Fig. 6.

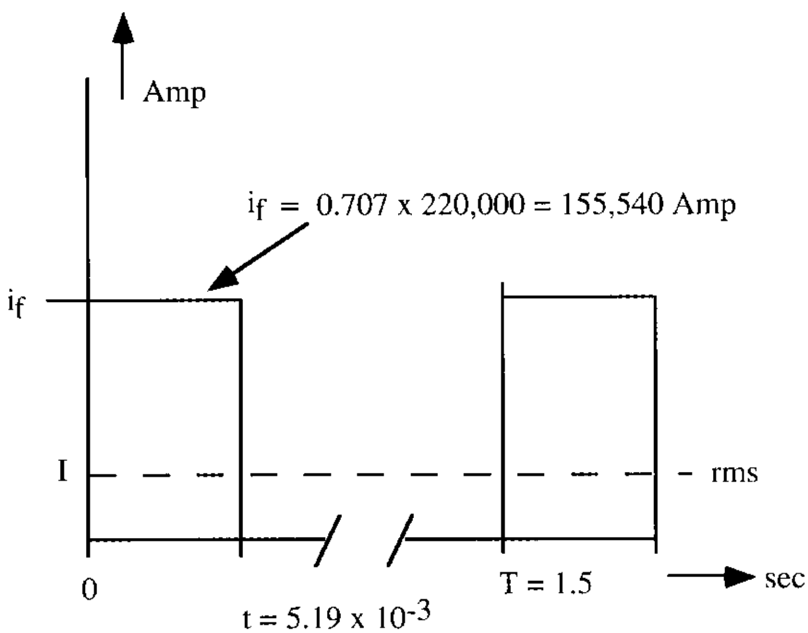


Figure 6: rms equivalent pulse train of Fig. 5.

$$I = i_r \sqrt{\frac{t}{T}}$$

$$I = 155{,}540 \sqrt{\frac{5.19 \times 10^{-3}}{1.5}}$$

The rms value I of the current pulse train through the horns is:

$I = 9150$ A

3.6 Estimated power losses caused by the pulse train

$P_{loss} = (9150)^2 \; 1.524 \times 10^{-3}$

The estimated circuit power losses caused by the current pulse train are:

$P_{loss} \sim 128\text{kW}$

The water cooling needed to remove 128 kW of losses is about 15 GPM.

3.7 Power supply requirements

The power supply ratings can now be estimated as below:

power supply average output	125 kW
peak output voltage	1400 Vdc
peak output current	140.8 A
recommended power supply rating	200 kW

Estimate the required peak output current of the power supply as below:

Capacitor bank to be charged	333,000 μF
Recovered charge voltage at start of charging	850 Vdc
Final charge voltage	1400 Vdc
Choose to make up capacitor charge loss in	1.3 sec

The required charge current can be calculated from this information:

The required rate of charge voltage increase is $\frac{1400-850}{1.3} = 423$ V/sec

The charge current $i = \frac{dQ}{dt} = C\frac{dV}{dt}$ (constant current charging)

The required charging current i = 0.333 x 423 = 140.8 A.

Conclusion: A constant charging current of 140.8 A and 1.3 sec duration is enough to restore the capacitor bank charge to 1400 V after a discharge. Fermilab's 240 kW beamline power supplies can be set at 300 A, 800 V. Two such power supplies in series would cover the required charging power supply rating. The center connection between the power supplies, or the connection between the horns, should be connected to ground. This ground point will keep the peak system voltage to ground to about 800 V or less.

3.8 Discharge switch estimates

The discharge SCR's (Fig. 1) need a more thorough investigation than the few comments below, but SCR GE#C781LA looks reasonable.

SCR #C781LA ratings: Voltage : 2100 V (a little low)
I_{rms}: 3925 A
1 cycle 60 Hz surge non repetitive : 45,000 A

The capacitor bank needs to be understood before a final SCR choice can be made. Let us choose to use 8 capacitor bank cells in parallel and thus 8 switches in parallel. The operating values/switch SCR are:

$\hat{i}$ = 27,500 A
V = 1400 V
$I_{rms/SCR}$ = 562 A

The estimated cost per switch including all heatsinks and clamps is:

cost/switch = \$3,000/switch or \$6,000/switch with reversing.

3.9 Capacitor bank description

The design of the capacitor bank is the most crucial. The capacitor bank supplies high current pulses and needs high rms current rated capacitors. Manufacturers should initially be contacted for recommendations about the proposed capacitor choice and the number of cells from which the total capacitor bank can be safely constructed. Other circuit components can be chosen to match the capacitor bank layout.

The operating requirements for the capacitor bank are:

capacitance	333,000 μF
type	energy discharge
discharge frequency	100 Hz
life expectancy	10^7 shots with 95% survival?
charge voltage	1400 V
reverse recovered voltage	60%
final reverse charge	100%
operation	bipolar
peak discharge current	220,000 A
rms value of discharge current	9000 A
discharge pulse period	1.5 sec
stored energy	233 kJoules
capacitor case rupture energy	*

*Needs to be known to find the number of capacitor cases that can be put safely in parallel.

Below are some estimates for the capacitor bank. A typical capacitor may be as follows:

stored energy:	2 Joules/inch^3
weight:	0.03 lbs/Joule
cost:	$2/Joule

The total capacitor bank of 330,000 μF would be about:

volume:	$\frac{233,000}{2}$ ~ 120,000 inch^2 or 70 ft^3
final size:	volume x fill factor ~ 140 ft^3 or about 8' H x 12' L x 1-1/2' D
weight:	7,000 lbs plus structural
capacitor cost:	$660,000 *
capacitor structural:	$40,000
TOTAL CAPACITOR BANK:	**$700,000**

*A preliminary estimate supplied by GE, 1/11/94, indicates a capacitor cost of $103,000.

3.10 Rough system cost estimates (horns not included)

		K$
1	power supply 1400 V - 200 kW with charge polarity switch	125
2	capacitor bank 333,000 μF, 2000 V 9150 A rms	700 *
3	40 m transmission line water cooled	15
4	8 SCR switches (no reversing)	24
5	8 current XDTR's, 30,000 A (LEM)	16
6	discharge resistor and safety system	15
7	firing circuits and controls	10
8	cables	10
9	watercooling	5
10	installation labor	60
11	contingency	20
	TOTAL: 1 MILLION DOLLARS	

*A preliminary estimate supplied by GE, 1/11/94, indicates a capacitor cost of $103,000.

4.0 FINAL CONCLUSION AND COMMENT

A system without a coupling transformer seems practical. A design using a transformer with a secondary winding rated 9150 A rms, 220,000 A peak at 1400 V peak will be very expensive. I do not know what it would cost. The transformer would add leakage inductance and resistance to the circuit. The losses would therefore be higher. Lowering the inductance of this preliminary design would reduce the cost.

General Electric Company supplied a preliminary capacitor cost estimate of $103,000 compared to a capacitor cost estimate of $660,000 shown in Section 3.9. The estimate supplied by General Electric is probably more realistic and indicates that the total system could be built for an estimated amount of $500,000.